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14. ABSTRACT

Many computationally challenging problems can be reduced to Quadratic Unconstrained Binary Optimization (QUBO), which can be solved by a quantum evolution from a strong transverse field to a spin glass Hamiltonian (also known as quantum annealing or QA). We have examined open system QA, using theoretical and experimental techniques to deepen our understanding of open system QA by situating it in the context of related, well studied classical and quantum problems. We have explored and elucidated the significance of tunneling in QA with Path

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Report Title

Final Report: Optimization Via Open System Quantum Annealing

ABSTRACT

Many computationally challenging problems can be reduced to Quadratic Unconstrained Binary Optimization (QUBO), which can be solved by a quantum evolution from a strong transverse field to a spin glass Hamiltonian (also known as quantum annealing or QA). We have examined open system QA, using theoretical and experimental techniques to deepen our understanding of open system QA by situating it in the context of related, well studied classical and quantum problems. We have explored and elucidated the significance of tunneling in QA with Path Integral Monte Carlo. We have also provided signatures of quantum behavior of QA against closely related simulated annealing implementations, analytically, numerically, and experimentally. We have carried out a comprehensive comparison of geometrically-local open-system QA and classical solvers for computationally hard problems such as MAX-2-SAT. We have exploited and further developed a graph-theoretical mapping between the Ising spin glass partition function and circuit model decision problems, discovered in a previous ARO Quantum Algorithms funded project. We have made significant progress on error correction techniques for QA, both theoretically and experimentally, and in demonstration of quantum speedup.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/20/2013	1.00	Sergio Boixo, Tameem Albash, Federico M. Spedalieri, Nicholas Chancellor, Daniel A. Lidar. Experimental signature of programmable quantum annealing, Nature Communications, (06 2013): 0. doi: 10.1038/ncomms3067
08/27/2014	6.00	T. F. Ronnow, Z. Wang, J. Job, S. Boixo, S. V. Isakov, D. Wecker, J. M. Martinis, D. A. Lidar, M. Troyer. Defining and detecting quantum speedup, Science, (06 2014): 0. doi: 10.1126/science.1252319
08/27/2014	7.00	Kevin Young, Robin Blume-Kohout, Daniel Lidar. Adiabatic quantum optimization with the wrong Hamiltonian, Physical Review A, (12 2013): 0. doi: 10.1103/PhysRevA.88.062314
08/27/2014	8.00	Daniel A. Lidar, Milad Marvian, Tameem Albash, Paolo Zanardi. Fluctuation theorems for quantum processes, Physical Review E, (09 2013): 0. doi: 10.1103/PhysRevE.88.032146

TOTAL: 4

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/21/2013	2.00	Kristen Pudenz, Tameem Albash, Daniel Lidar. Error corrected quantum annealing with hundreds of qubits, (07 2013)
08/21/2013	5.00	Siddhartha Santra, Gregory Quiroz, Greg Ver Steeg, Daniel Lidar. MAX 2-SAT with up to 108 qubits, arXiv:1307.3931 (07 2013)
08/21/2013	4.00	Sergio Boixo, Troels F. Rønnow, Sergei V. Isakov, Zhihui Wang, David Wecker, Daniel A. Lidar, John M. Martinis, Matthias Troyer. Quantum annealing with more than one hundred qubits, arXiv:1304.4595 (04 2013)
08/21/2013	3.00	Lei Wang, Troels F. Rønnow, Sergio Boixo, Sergei V. Isakov, Zhihui Wang, David Wecker, Daniel A. Lidar, John M. Martinis, Matthias Troyer. Comment on: "Classical signature of quantum annealing", arXiv:1305.5837 (05 2013)
08/27/2014	9.00	Itay Hen. Quantum Gates with Controlled Adiabatic Evolutions, EPL (Europhysics Letters) (06 2014)

TOTAL: **5**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
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Total Number:	

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Names of Under Graduate students supported

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Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

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Names of Personnel receiving masters degrees

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Total Number:

Names of personnel receiving PHDs

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Names of other research staff

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Inventions (DD882)

Scientific Progress

Technology Transfer

Final Progress Report

Optimization via Open System Quantum Annealing

Grant number W911NF-12-1-0523

Forward

Title: Optimization via Open System Quantum Annealing

Principal Investigators: Sergio Boixo (now at Google), Robert Lucas, Daniel Lidar, and Itay Hen

Senior Investigators: Greg Ver Steeg

Postdoctoral Associates: Zhihui Wang, Tameem Albash, Iman Marvian, and Walter Vinci

Graduate Students: Gregory Quiroz, Kristen Pudenz, Anurag Mishra, Milad Marvian, Joshua Job, and Siddhartha Muthukrishnan

Type of Award: 62383-PH-QC

Start Date: 9/1/2012
End Date: 8/31/2015

Statement of problems studied:

Main Project Goals: Theoretically, numerically, and experimentally investigate the performance of a computational framework based on open system quantum annealing.

Project Description:
Many computationally challenging problems can be reduced to Quadratic Unconstrained Binary Optimization (QUBO), which can be solved by a quantum evolution from a strong transverse field to a spin glass Hamiltonian (also known as quantum annealing or QA). Closed system QA has been shown to provide quantum speedups for some final Ising-like Hamiltonian problems. Building upon previous efforts, we have addressed open system QA. Our goal was to use theoretical and experimental techniques to deepen our understanding of open system QA by situating it in the context of related, well studied classical and quantum problems. We have explored and elucidated the significance of tunneling in QA with Path Integral Monte Carlo. We have also provided signatures of quantum behavior of QA against closely related simulated annealing implementations, analytically, numerically, and experimentally. We have carried out a comprehensive comparison of geometrically-local open-system QA and classical solvers for computationally hard problems such as MAX-2-SAT. We have exploited and further developed a graph-theoretical mapping between the Ising spin glass partition function and circuit model decision problems, discovered in a previous ARO Quantum Algorithms funded project. We have made significant progress on error correction techniques for QA, both theoretically and experimentally. Finally, we have worked to demonstrate a genuine experimental quantum speedup in open system QA.

Problems studied:

1. **Benchmarking of the D-Wave Two Experimental Quantum Annealer [5,18,19,20].** We have been studying the performance of the frist two generations of D-Wave processors at the USC – Lockheed Martin Quantum Computing Center using random Ising spin problems, comparing them against classical exact and heuristic solvers. We have also been improving its performance via error correction, and using it as a tool study phase transitions in satisfiability problems. We have engineered frustrated problems with planted solutions that on the one hand are known to be difficult to solve using heuristic classical solvers, but on the other hand have known ground state energies. We have shown that unlike the case for easy random Ising problems, experimental quantum speedups cannot be ruled out for these carefully designed problems.
2. **Determining the underlying physics of experimental quantum annealer [8,10].** We have developed the theoretical framework required for the incorporation of the effects of a decohering environment into finite temperature annealing processes. By carefully considering and employing certain approximations, we have come up with an open system physical model whose predictions agree very well with the outcome of the D-Wave Two quantum annealer. Along the way, we were also able to rule out every classical model that has so far been proposed as the underlying physical mechanism driving the D-Wave chips.
3. **Characterization of quantum annealers and "quantum signatures" [4,7,15,25].** We have devised D-Wave-embeddable Ising toy problems that allowed us,

based on the output of the device, to distinguish quantum annealing from its classical counterparts. By constructing Ising-type problems that exhibit different quantum and classical energy landscapes, and subsequently running them on the D-Wave chip as well as on a suite of classical models, we were able to detect mechanisms and "quantum signatures" of the D-Wave chip.

We have also developed methods to measure the susceptibility of experimental quantum annealers to classical thermal hardness thereby characterizing the "classicality" of experimental quantum annealers. By classifying random Ising problems according to their classical thermal hardness, we have shown that the D-Wave chip is very susceptible to changes in the thermal hardness of random Ising problems.

4. **Theoretical AQC [1,2,3,11,13,16,17,24].** We have developed theoretical schemes to improve the performance and boost the practicality of future quantum annealing optimizers. In one study, we developed models that combine the modularity of the gate model with some of the robustness of adiabatic quantum computation. In another, we showed that certain driver Hamiltonians may be used to boost the encodability of many constrained optimization problems. We examined the role of tunneling as a speedup mechanism in permutation symmetric Hamming weight optimization problems, and identified a different mechanism, which we call a "diabatic cascade", that can result in quantum speedups. We developed an open system analogue to the adiabatic theorem of quantum mechanics and generalized the Jarzynski equality to the setting of quantum channels.

5. **Quantum annealing error correction [6,9,14,21,22,23].** We have devised error correction methods to increase the fault-tolerance of analog quantum annealers and reduce their error rates. We have analyzed these methods theoretically using mean field models and shown that they work by softening the closing of the quantum critical gap, and by allowing certain excited states to encode correct answers. We have devised several different quantum annealing correction schemes and worked to optimize the various parameters of each method on the D-Wave chips as well as on simulations of quantum annealing optimizers. We have also tested each scheme on different types of problems, e.g., chains and randomly generated instances. In this effort, we have also looked at the effects of analog errors on the performance of experimental quantum annealing optimizers and methods to correct these.

6. **Solving practical problems on experimental quantum annealers [1,6,19].** We have studied different schemes for the embedding of practical problems (e.g., MAX2SAT), that are not directly embeddable on fixed sparse qubit layouts. By combining these with quantum annealing error correction schemes we now have ways to embed practical problems of importance of the Government, Industry and Academia on experimental quantum annealing devices.

7. **Quantum annealing beyond speedup.** We have begun looking into potential quantum enhancements that do not directly correspond to quantum speedups. Since quantum annealers are in fact samplers of configurations from distributions that are potentially hard to simulate classically, we have worked to leverage this property to provide certain quantum advantages such as solution counting and other objectives that do not translate directly to quantum speedups. We have also been utilizing the fact that quantum annealers provide configurations that are potentially hard to generate classically,

in order to train machine learning classifiers based on a mapping from machine learning to the Ising model.

Summary of the most important results

Major Completed Project Milestones:

- Found signatures of entanglement for D-Wave's Vesuvius QA processor
- Studied scaling of computational difficulty for Ising and Max-2-Sat problems with up to 108 qubits.
- Compared the physics of the D-Wave chip to both simulated annealing and simulated quantum annealing, demonstrating significant similarity to the latter.
- Benchmarked upgraded QA chip with over 500 qubits.
- Tested feasibility of error correction for open system QA.
- Identified classically difficult problems to look for QA speedup.
- Demonstrated error correction effectiveness.
- Demonstrated quantum annealing correction on antiferromagnetic chains, with substantial fidelity gains
- Benchmarked D-Wave Two on random Ising instances
- Ruled out several classical models for the D-Wave One and demonstrated agreement with simulated quantum annealing
- Studied applications of QA to classically difficult problems.
- Devised classically hard problems.
- Developed quantum open system adiabatic theorems.
- Developed hybrid gate-model/adiabatic formalism.
- Provided theoretical analysis and explanation for error correction effectiveness.
- Studied quantum annealing correction for random Ising instances
- Studied quantum speedup using the D-Wave Two processor
- Studied the role of tunneling in providing quantum annealing speedup over classical algorithms
- Characterized the effects of classical hardness on the performance of experimental quantum annealers.

Appendix A: Publications

1. I. Hen and F. M. Spedalieri, “Quantum annealing for constrained optimization”, submitted for publication, arXiv:1508.04212 (2015).
2. I. Hen, “Quantum gates with controlled adiabatic evolutions”, *Phys. Rev. A* 91, 022309 (2015).
3. A. Kalev and I. Hen, “Fidelity-optimized quantum state estimation”, *New Journal of Physics* 17 092008 (2015).
4. I. Hen and V. Martin-Mayor, “Unraveling Quantum Annealers using Classical Hardness”, accepted for publication in *Scientific Reports*, arXiv:1502.02494 (2015).
5. I. Hen, J. Job, T. Albash, Troels F. Roennow, M. Troyer, D. A. Lidar, “Probing for quantum speedup in spin glass problems with planted solutions”, *Phys. Rev. A*. 92, 042325 (2015).
6. W. Vinci, T. Albash, G. Paz-Silva, I. Hen and D. A. Lidar, “Quantum annealing correction with minor embedding”, *Phys. Rev. A* 92, 042310 (2015)..
7. T. Albash, W. Vinci, A. Mishra, P.A. Warburton, and D.A. Lidar, “Consistency tests of classical and quantum models for a quantum annealer”, *Phys. Rev. A* 91, 042314 (2015).
8. T. Albash and D.A. Lidar, “Decoherence in adiabatic quantum computation”, *Phys. Rev. A* 91, 062320 (2015).
9. K. Pudenz, T. Albash, and D.A. Lidar, “Quantum Annealing Correction for Random Ising Problems”, *Phys. Rev. A* 91, 042302 (2015).
10. T. Albash, T. Ronnow, M. Troyer, D.A. Lidar, “Reexamining classical and quantum models for the D-Wave One processor”, *The European Physics Journal, Special Topics* 224, 111 (special issue on quantum annealing) (2015).
11. S. Muthukrishnan, T. Albash, and D.A. Lidar, “Tunneling and speedup in quantum optimization for permutation-symmetric problems”, submitted for publication, arXiv:1511.03910 (2015).
12. S. Matsuura, H. Nishimori, T. Albash, D.A. Lidar, “Mean Field Analysis of Quantum Annealing Correction”, submitted for publication, arXiv:1510.07709 (2015).
13. L.C. Venuti, T. Albash, D. A. Lidar, and P. Zanardi, “Adiabaticity in open quantum systems”, submitted for publication, arXiv:1508.05558 (2015).
14. A. Mishra, T. Albash, D.A. Lidar, “Performance of two different quantum annealing correction codes”, accepted for publication in *Q. Info. Proc*., arXiv:1508.02785 (2015).
15. T. Albash, I. Hen, F. M. Spedalieri, D. A. Lidar, “Reexamination of the evidence for entanglement in the D-Wave processor”, accepted for publication in *Phys. Rev. A*, arXiv:1506.03539 (2015).
16. I. Hen, “Fourier-transforming with quantum annealers”, *Front. Phys*. 2, 44 (2014).
17. I. Hen, “Period finding with Adiabatic Quantum Computation”, *Europhysics Letters* 105, 50005 (2014).
18. T. F. Rønnow, Z. Wang, J. Job, S. Boixo, S.V. Isakov, D. Wecker, J.M. Martinis, D.A. Lidar, M. Troyer, “Defining and detecting quantum speedup”, *Science* 345, 420 (2014).
19. S. Santra, G. Quiroz, G. Ver Steeg, D.A. Lidar, “MAX 2-SAT with up to 108 qubits”, *New J. Phys*. 16, 045006 (2014).

20. S. Boixo, T. Ronnow, S. Isakov, Z. Wang, D. Wecker, D.A. Lidar, J. Martinis, M. Troyer, “Quantum Annealing With More Than One Hundred Qubits”, *Nature Phys*. 10, 218 (2014).
21. K. L. Pudenz, T. Albash, D.A. Lidar, “Error corrected quantum annealing with hundreds of qubits”, *Nature Commun*. 5, 3243 (2014).
22. I. Marvian and D.A. Lidar, “Quantum error suppression with commuting Hamiltonians: Two-local is too local”, *Phys. Rev. Lett*. 113, 260504 (2014).
23. K.C. Young, R. Blume-Kohout, D.A. Lidar, “Adiabatic quantum optimization with the wrong Hamiltonian”, *Phys. Rev. A* 88, 062314 (2013).
24. T. Albash. D.A. Lidar, M. Marvian, P. Zanardi, “Fluctuation theorems for quantum processes”, *Phys. Rev. E*. 88, 032146 (2013).
25. S. Boixo, T. Albash, F.M. Spedalieri, N. Chancellor, and D. Lidar, “Experimental Signature of Programmable Quantum Annealing”, *Nature Comm*. 4, 2067 (2013).

Appendix B: Presentations (partial list)

Presentations by Daniel Lidar:
Colloquia, Keynote Talks, Plenary Talks, and Public Lectures

06/15 Distinguished Guest Speaker IEEE CLAS Computer Society, Loyola Marymount University, CA
06/15 Talk at Dreamworks Animation, Glendale, CA
02/15 Physics Colloquium, UCLA
01/15 Google Tech Talk, Venice Beach, CA
09/14 Physics Colloquium, Texas A&M University
05/14 Electrical Engineering Colloquium, UC Riverside
01/14 QuAIL (Quantum Artificial Intelligence Laboratory) Colloquium, NASA Ames, Palo Alto
02/13 Lockheed Martin Palo Alto Colloquium
02/13 Boeing Distinguished Researcher And Scholar Seminar (B-DRASS) series, Huntington Beach, California
10/12 USC Viterbi School of Engineering Undergraduate Honors Colloquium

Invited talks at Conferences, Workshops, Summer/Winter Schools, and Programs

08/15 Conference for Quantum Information and Quantum Control, Toronto, Canada
08/15 New Horizons of Quantum and Classical Information 2015 (NHQCI2015), Tokyo Institute of Technology (presented by postdoc Walter Vinci)
07/15 Fourth Conference in Adiabatic Quantum Computing (AQC 2015), ETH Zurich, Switzerland
03/15 Annual APS March meeting, Tutorial on Quantum Annealing
12/14 Quantum Sensing, Metrology, and Algorithms Workshop, Northrop Grumman, Los Angeles
07/14 Shortcuts to Adiabaticity, Optimal Quantum Control, and Thermodynamics

Conference, Telluride, Colorado
03/14 Advances in Quantum Algorithms and Computation, Aspen Center for Physics, Colorado
02/14 MURI retreat, Laguna Beach
01/14 DSRC/DARPA Quantum Entanglement Workshop
06/13 International Workshop on Frontiers in Quantum Information Science (QIS-2013), Fudan University, Shanghai, China (presented by postdoc Zhihui Wang)
06/13 Science Foo Conference, Google, Palo Alto, California
05/13 Workshop on complex networks and quantum information, Perimeter Institute, Waterloo, Canada
03/13 KITP Workshop on Control of Complex Quantum Systems, UCSB, Santa Barbara, California
03/13 International Conference on Adiabatic Quantum Computing (AQC 2013), London

Seminars

06/15 Solid State Physics Seminar, Hebrew University of Jerusalem, Israel
05/15 Condensed Matter Physics Seminar, UC San Diego
05/14 Seminar at D-Wave Systems, Burnaby, BC, Canada
04/14 Berkeley Quantum Information and Computation Seminar, UC Berkeley, CA
04/14 Army Research Lab seminar, Aberdeen, MD
08/13 Quantum seminar, Tel Aviv University, Israel
08/13 CWI seminar, Amsterdam University, The Netherlands
05/13 Electrical Engineering seminar, Princeton University
05/13 Physical Chemistry seminar, MIT
08/12 Kavli Institute of nanoscience seminar, Delft, The Netherlands
08/12 Quantum control seminar, Princeton University

Presentations by Itay Hen:

Colloquia, Invited Talks, and Public Lectures

- 11/15 Rethink Disruption CTO Forum, San Francisco, CA.
- 05/15 QCD: from Theory to Experiment (symposium in honor of Marek Karliner's 60th birthday), Tel Aviv University, Tel Aviv, Israel.
- 02/15 Peter Young Retirement Conference, Santa Cruz, CA.
- 09/14 D-Wave Users Colloquium, Sunnyvale, CA.
- 09/14 Practical Applications of Quantum Annealing Workshop, Griffiss Air Force Base, Rome, NY.
- 08/14 Workshop on heuristic and quantum-inspired optimization, Zurich, Switzerland.
- 07/14 2014 OLCF Users Meeting, Oak Ridge, TN.
- 06/14 Third Workshop on Adiabatic Quantum Computation, USC, Los Angeles.

- 03/14 Aspen Winter Conference on Advances in Quantum Algorithms and Computation, Aspen.
- 02/14 Physics Colloquium, University of Southern California, Los Angeles, CA.
- 01/14 3rd D-Wave Application Colloquium, Google Venice, Los Angeles, CA.

Conferences, Workshops, Summer/Winter Schools, and Programs
- 11/15 International Conference for High Performance Computing (SC15, USC exhibit), Austin, TX.
- 09/15 D-Wave/Lockheed-Martin/USC Meeting, University of Southern California, Los Angeles, CA.
- 06/15 Fourth Conference in Adiabatic Quantum Computing, ETH Zurich, Switzerland.
- 03/15 APS March Meeting, San Antonio, TX.
- 02/15 SQuInT (Southwest Quantum Information and Technology), Berkeley, CA.
- 02/15 Quantum Control MURI Retreat, Huntington Beach, CA.
- 08/14 ARO Program Review, Arlington VA.
- 03/14 APS March Meeting, Denver, CO.
- 02/14 Southwest Quantum Information and Technology (SQuInT), Santa Fe, NM.
- 02/14 Quantum Control MURI retreat, Laguna Beach, CA.

Seminars
- 04/15 Physics Seminar, San Jose State University, San Jose CA.
- 04/15 Condensed-Matter seminar, Bar-Ilan University, Ramat Gan, Israel.
- 10/14 Lawrence Livermore National Laboratory, Livermore, CA.
- 06/14 Google’s Quantum Computing Group, Venice, CA.
- 01/14 Quantum Seminar, Tel-Aviv University, Tel Aviv, Israel, January 2014.
- 12/13 Condensed Matter Seminar, Ben-Gurion University, Be’er Sheva, Israel.
- 12/13 Google’s Quantum Computing Group, Venice, CA.